

**Titre:** Flooding of the Saguenay region in 1996. Part 2: Aux Sables River  
Title: flood mitigation and environmental impact assessment

**Auteurs:** Eman AlQasimi, Pierre Pelletier, & Tewfik Mahdi  
Authors:

**Date:** 2019

**Type:** Article de revue / Article

**Référence:** AlQasimi, E., Pelletier, P., & Mahdi, T. (2019). Flooding of the Saguenay region in 1996. Part 2: Aux Sables River flood mitigation and environmental impact assessment. Natural Hazards, 96 (1), 17-32. <https://doi.org/10.1007/s11069-018-3444-3>  
Citation:

## Document en libre accès dans PolyPublie

Open Access document in PolyPublie

**URL de PolyPublie:** <https://publications.polymtl.ca/5312/>  
PolyPublie URL:

**Version:** Version finale avant publication / Accepted version  
Révisé par les pairs / Refereed

**Conditions d'utilisation:** Tous droits réservés / All rights reserved  
Terms of Use:

## Document publié chez l'éditeur officiel

Document issued by the official publisher

**Titre de la revue:** Natural Hazards (vol. 96, no. 1)  
Journal Title:

**Maison d'édition:** Springer  
Publisher:

**URL officiel:** <https://doi.org/10.1007/s11069-018-3444-3>  
Official URL:

**Mention légale:** This is a post-peer-review, pre-copyedit version of an article published in Natural Hazards (vol. 96, no. 1) . The final authenticated version is available online at:  
Legal notice: <https://doi.org/10.1007/s11069-018-3444-3>

1 **Flooding of the Saguenay region in 1996: Part 2- flood mitigation**  
2 **and environmental impact assessment on Aux Sables River.**

3 *Eman AlQasimi<sup>1</sup>, Pierre Pelletier<sup>2</sup> and Tew-Fik Mahdi<sup>3\*</sup>*

4 <sup>1</sup> PhD candidate, Ecole Polytechnique de Montreal, Department of  
5 Civil, Geological and Mining.C.P.6097, Succ. Centre-Ville, Montreal,  
6 Québec, H3C 3A7. Canada

7 <sup>2</sup> Project manager, WSP, 1135, boul. Lebourgneuf, Quebec  
8 (Quebec) G2K 0M5 CANADA

9 <sup>3</sup> Professor, Ecole Polytechnique de Montreal, Department of Civil,  
10 Geological and Mining.C.P.6097, Succ. Centre-Ville, Montreal,  
11 Quebec, H3C 3A7. Canada

12

13 **Abstract.** After the flooding of the Saguenay region in July 1996,  
14 several rivers, including the Aux Sables River, experienced unusual  
15 water discharges causing flooding and morphological damages. This  
16 paper deals with flood mitigation and environmental impact  
17 assessment in Aux Sables River following the July 1996 flooding. The  
18 consequences of the flood are summarized, followed by different  
19 proposed solutions for a similar flood are reviewed. For Aux Sables  
20 River, the option of digging the river to increase the discharge without  
21 causing flooding brings the issue of suspended sediment concentration  
22 since the intake water at Jonquiere will be at risk. Thanks to a newly  
23 developed software, UMHYSER-1D, suspended sediment impact  
24 assessment in Aux Sables River provides the maximum permissible  
25 sediment discharge to be released in the river to avoid any risk  
26 pollution for the population of Jonquiere city. Using UMHYSER-1D  
27 to mitigate water pollution risk confirms the important role of  
28 numerical modeling in solving complex engineering problems.

29 **Keywords:** Saguenay flood July 1996, Aux Sables River, Flood  
30 mitigation, Suspended sediment impact assessment, UMHYSER-1D.

---

\* Corresponding author: [Tewfik.Mahdi@polymtl.ca](mailto:Tewfik.Mahdi@polymtl.ca)

## 31    **1 Introduction**

32    During the July 1996 Saguenay flood, several rivers experienced  
33    unusual water discharges causing flooding and morphological  
34    damages. On top of the impacts to the Ha! Ha! River (Brooks and  
35    Lawrence, 1999; Lapointe et al., 1998), the most extreme flooding  
36    occurred along the rivers Aux Ecorces, Pikauba, and Cyriac, which  
37    flow into Lac Kénogami, and are tributaries of the Aux Sables and  
38    Chicoutimi rivers, Du Moulin and A Mars Rivers (Figure 1). The  
39    Chicoutimi and Aux Sables Rivers, two outlets of the Kenogami  
40    reservoir, were particularly affected by the flooding.

41    For Lake Kenogami, the estimated maximum inflow was 2780 m<sup>3</sup>/s,  
42    exceeding the outflow and causing the reservoir to rise to  
43    unprecedented levels. The water level reached a maximum level of  
44    166.08 m, exceeding the crest of the concrete dams, 165.7 m  
45    (Environnement et Faune Quebec, 1996a). As a result, a number of  
46    dykes and all three dams (two discharging in Aux Sables River)  
47    controlling the reservoir level were overtopped by Lac Kenogami  
48    waters (Environnement et Faune Quebec, 1996a). The outflow spills  
49    primarily into Aux Sables and Chicoutimi Rivers.

50    The four sections of this paper deal with flood mitigation and  
51    environmental impact assessment in Aux Sables River. Section 2

52 presents first, the consequences of the 1996 flood on the Aux Sables  
53 River, then the proposed solutions to reduce them, for a similar flood,  
54 are reviewed and the retained option is explained. Section 3 deals with  
55 the suspended sediment impact assessment of suspended sediment in  
56 Aux Sables River during the implementation of the retained solution.  
57 The results and discussion are presented in section 4, followed by a  
58 conclusion.

59

## 60 **2 Aux Sables River flood mitigation**

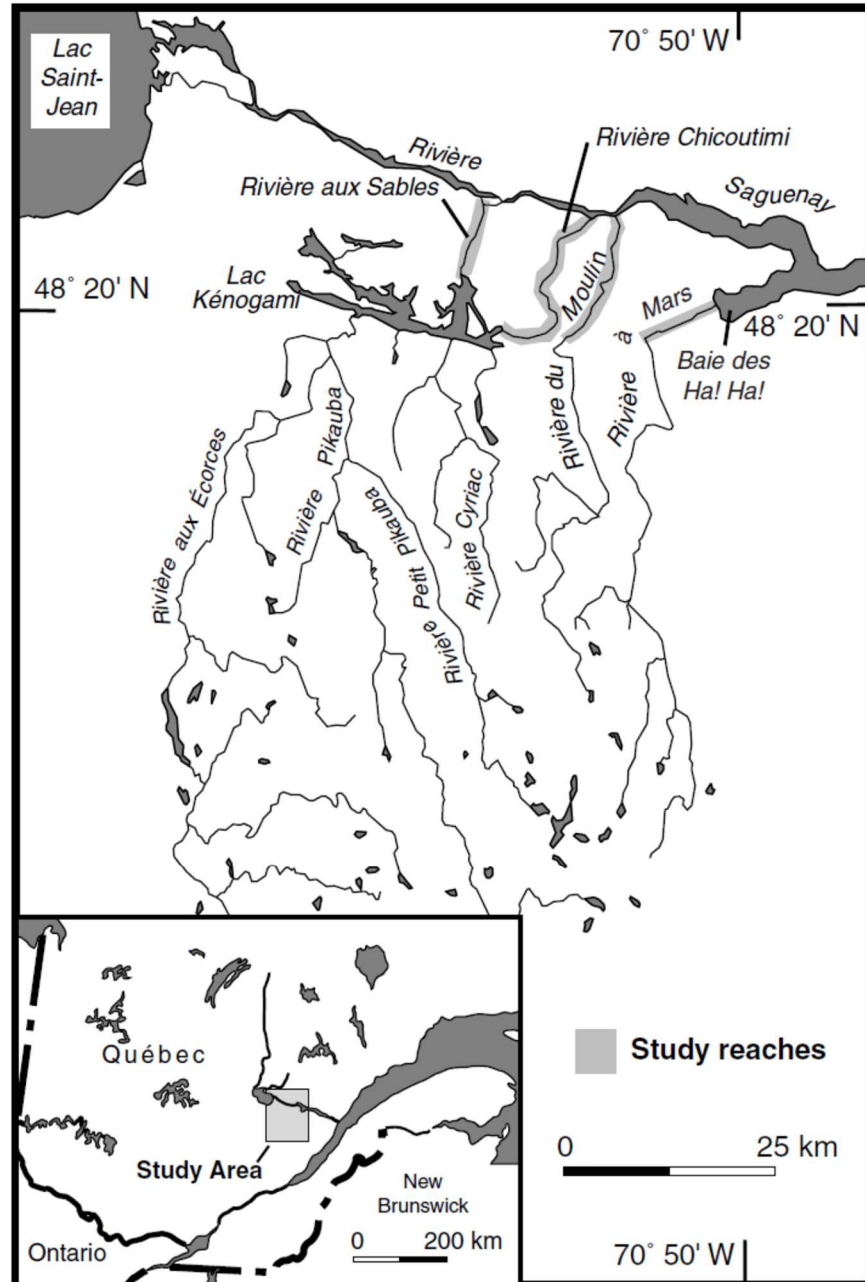
### 61 **2.1 Study reach**

62 Flowing northwards into the Saguenay valley, the Aux Sables River is  
63 a tributary of the Saguenay River (Figure 1). The study reach is  
64 situated along the lower 11.1 km of the Aux Sables River, from the  
65 Lake Kenogami to the Saguenay River, with three run-of-the-river  
66 dams: Jonquière dam, Ville-de-Jonquière dam and Chute-à-Besy dam  
67 (Figure 2).

68

69 The longitudinal profile of the river is shown in figure 3 where the  
70 gentle river gradient steepens markedly along the last 3 km,  
71 characterized by the presence of bedrock.

72



73  
 74 Figure 1. Location map depicting Lake Kenogami, Chicoutimi and  
 75 Aux Sables Rivers (Brooks and Lawrence, 2000).

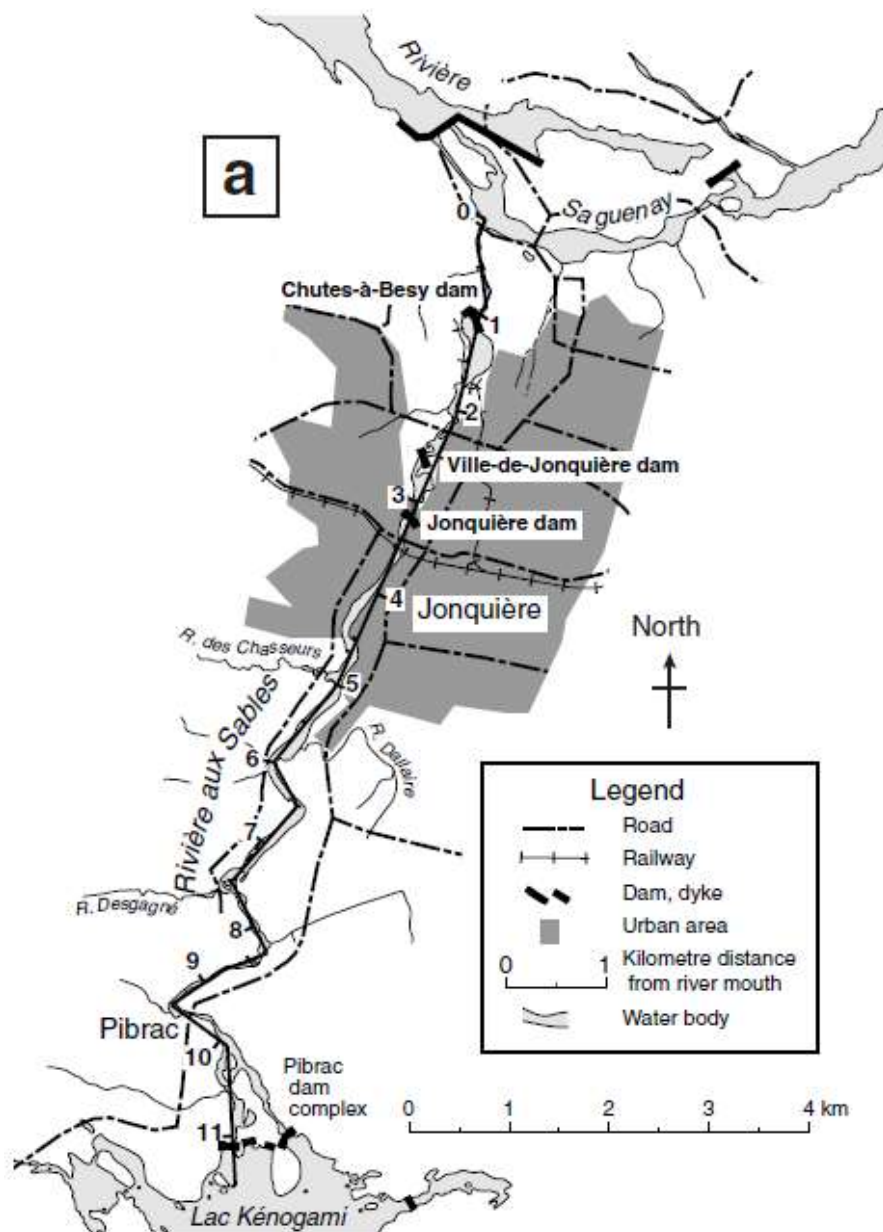


FIGURE 2. Aux Sables River: Pre-flood maps depicting the study reach along with the location of the run-of-the-river dams (Modified after Brooks and Lawrence, 2000).

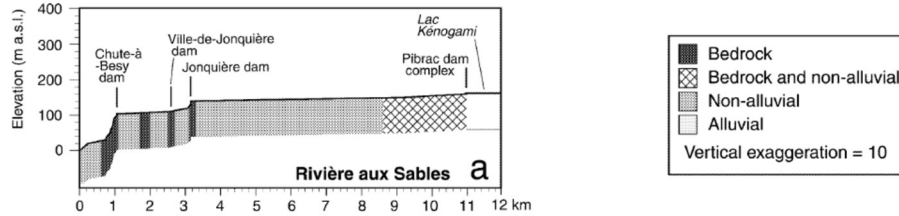


FIGURE 3. Longitudinal profiles and channel morphologies along the Aux Sables River (Modified after Brooks and Lawrence, 2000).

## 2.2 Discharge

The discharges on the two rivers, Aux Sables and Chicoutimi, outlets of the reservoir Kenogami, are regulated by control dams at the reservoir. The rainstorm of July 18 to 21, 1996, produced the hydrograph in figure 4, on Aux Sables River where two control dams and two dikes form the Pibrac dam complex (Figure 2).

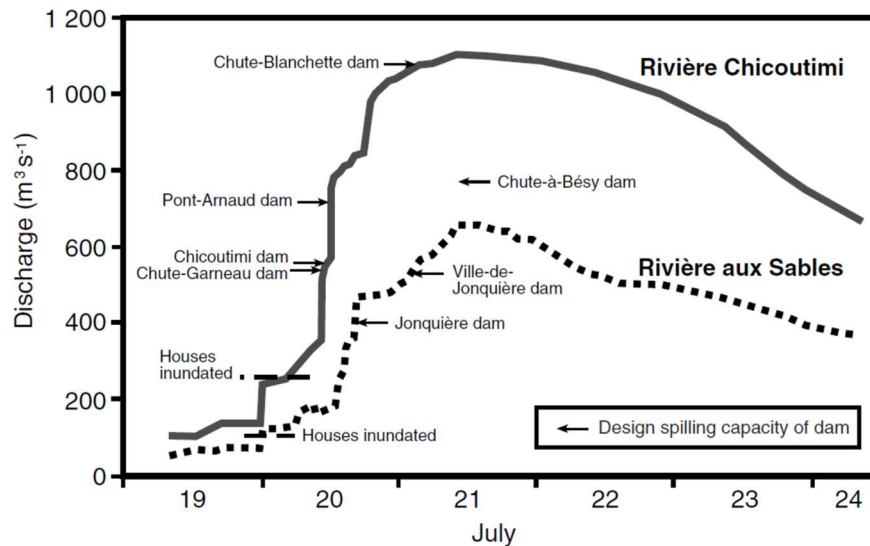


FIGURE 4. Aux Sables River's storm hydrograph (July 19-24, 1996; CSTGB, 1997). Note the minimum discharge beyond which houses begin to be flooded and the maximum spilling capacities of the run-of-the-river dams (Modified after Brooks and Lawrence, 2000).

## 98    **2.3 Consequences**

99    Along Aux Sables River, when the discharge reaches 150 m<sup>3</sup>/s, the  
100    inundation of property occurs and when 170 m<sup>3</sup>/s are exceeded,  
101    flooding of homes begin (Environnement et Faune Quebec, 1996a).  
102    During the July 1996 flooding, not only was the peak flow discharge  
103    653 m<sup>3</sup>/s (CSTGB, 1997), overtaking these critical discharges, but  
104    also flood discharges exceeded the available spilling capacity at  
105    Jonquière dam and Ville-de-Jonquière dam, two run-of-the-river dams  
106    (figure 4). Table 1 summarizes the spilling capacities and the eventual  
107    consequences of the 3 dams. Between km 8.6 to 8.4, up to 20 m of  
108    lateral bank erosion occurred along the left bank, while a series of  
109    sand and gravel mid-channel, side, and point bars were aggraded  
110    between 8.3 and 7.2 km, and between km 0.6 and the river mouth (0  
111    km), the channel was widened from 20-30 m to 60-130 m. Between  
112    km 11 and 3.5, the gently-sloped upper portion of the river, along  
113    which numerous homes were inundated (Brooks et al., 1997).

114

115

116

117



118 Table 1. Aux Sables River's run-of-the-river dams and impacts from  
 119 flooding (modified after CSTGB, 1997 and Brooks and Lawrence,  
 120 2000).

Dam (Year)	Type (foundation)	Dam height (m)	Dam length (m)	Spilling capacity* (m <sup>3</sup> /s)	Impacts of flooding
Jonquière (1943)	Concrete gravity (bedrock with soil abutments)	8	93	530	- abutment breached, lateral valley side erosion, reservoir drained, river flow diverted away from dam
Ville-de- Jonquière (1996)	Concrete gravity (bedrock)	< 15	~105	455	- concrete wing- wall breached, partial drawdown of reservoir
Chute-à- Besy (1911)	Concrete gravity (bedrock) and earthen dike (soil)	< 15	~220	770	- dike breached, incision and lateral erosion of valley side, reservoir drained, river flow diverted away from dam

\* spilling capacity at maximum working level of reservoir

## 2.4 Flood mitigation

133    **Mitigation options**

134    The flooding events along the Aux Sables River, among other rivers,  
135    were analyzed by the ``Commission scientifique et technique sur la  
136    gestion des barrages`` (CSTGB, 1997). Afterward, Hydro-Quebec,  
137    Ministère de l'Environnement and a consortium of consultants  
138    assessed various options to mitigate flood, resulting from extreme  
139    conditions, in Lake Kenogami, Chicoutimi and Aux Sables Rivers  
140    (Ministère des Ressources Naturelles et Hydro-Québec, 2002a, 2002b,  
141    2002c, 2002d, 2002e; Hydro-Québec, 2001, 2002a, 2002b and  
142    Groupe-Conseil GÉNIVAR, 2002).

143    The options were analyzed according to the following criteria:

- 144    1.     A flood comparable to the one of July 1996 should not exceed  
145           the major flood levels on the Chicoutimi and Aux Sables  
146           Rivers, corresponding to the discharge beyond which a home  
147           begins to be flooded;
- 148    2.     For a maximum probable flood, water level of Lake Kenogami  
149           must be less than 166.67 m;
- 150    3.     All existing, or new, structures must conform to the Dam  
151           Safety Act ;
- 152    4.     During the summer, the water level of Lake Kenogami must be  
153           stabilized at  $163.86 \text{ m} \pm 0.1 \text{ m}$ .

154 Different scenarios were proposed. The first one proposed raising and  
155 consolidating the retaining structures of the Kenogami Lake, raising  
156 the flood levels on the rivers downstream and implementing an  
157 improved flood forecasting system.

158 The second scenario suggested the construction of a reservoir  
159 upstream of Kenogami Lake on the Pikauba River, the consolidation  
160 and modernization of existing structures of Kenogami Lake, and the  
161 construction of a sill in the Aux Sables River. In addition to the  
162 implementation of an improved flood forecasting system.

163 Finally, the third scenario involved the construction of two reservoirs  
164 on the Pikauba and the Aux Ecorces Rivers, the consolidation and  
165 modernization of existing structures of Kenogami Lake and the  
166 implementation of an improved flood forecasting system.

167

#### 168 **Digging a sill in Aux Sables River**

169 Relevant to this paper, only the flood mitigation option directly related  
170 to Aux Sables River will be reviewed. The following options were  
171 considered to increase Lake Kenogami's discharge capacity  
172 (Ministère des Ressources Naturelles, de la Faune et des Parcs, 2003):

173 5. Digging 600 m along the Aux Sables River;

174 6. Digging several kilometers along the Chicoutimi River;

- 175 7. Building an outlet toward Lake Saint-Jean along several  
176 kilometers via Belle-Rivière;  
177 8. Building a canal in the Jean-Dechêne stream which flows for  
178 several kilometers before reaching the Saguenay;  
179 9. Digging a tunnel several kilometers long toward the Saguenay.

180

181 After several studies, the retained option was digging a single sill in  
182 the Aux Sables River to ensure the protection of homes that are  
183 susceptible to flooding on either side of the river upstream of Pibrac  
184 Bridge (Ministère des Ressources Naturelles et Hydro-Québec, 2002a,  
185 2002b, 2002c, 2002d, 2002e). In 2009, GENIVAR (2009) proposed a  
186 new concept by eliminating the Pibrac Bridge's pillar (figure 5) which  
187 acts as an obstruction to the flowing water at high discharges.



188

189 Figure 5. Pibrac Bridge: for high discharges, the pillar is an  
190 obstruction to the flow, increasing the water level upstream. Note the  
191 cofferdam installed to limit suspended sediment release.  
192  
193 The proposed concept (figure 6) consists of:

- 194 1. Increase the flow section downstream of the bridge (downstream of  
195 km 10.29) by excavating the left bank for a length of about 60 m;
- 196 2. Increase the flow section to the right of the bridge by excavating the  
197 river bed of about 2 m and excavating on the left bank;
- 198 3. Replace the Pibrac Bridge with a span of 50 m (without central  
199 pillar);
- 200 4. Increase the flow section upstream of the bridge by excavating a  
201 channel of 440 m length, with a maximum width of 60 m, requiring  
202 an excavation of the river bed varying from 0.5 to 2 m;

203 According to the above, Aux Sables River will be able to carry a  
204 discharge of 650 m<sup>3</sup>/s without flooding the riparian houses.



Figure 6. Excavation limits from the Pibrac Bridge: yellow limits correspond to option replacing the bridge with a longer one with no pillar (Modified after GENIVAR, 2009).

### 3 Suspended sediment impact assessment

#### 3.1 Site description

The study area (figure 7) is about 5.8 km long, from the Pibrac Bridge (km 10.32) to the Jonquiere water intake (km 4.9). The outlet of the small shallow lake, just after the bridge (steep 400 m long reach), Rapid du CEPAL, forces suspended sediments mixing (figure 8). The tributaries to this river reach do not contribute significantly to the discharges of the river, except tributary C located at km 5.4, 500 m from the water intake station. As it can be seen in figure 9, the color difference between the water of this tributary and river's water, suggests that it provides substantial suspended sediment.







Figure 8. CEPAL rapid at km 9.7, looking upstream. Suspended sediment mixing allows adopting one-dimensional approach.



Figure 9. Suspended sediment inflow from tributary C (km 5.4) (Courtesy of GENIVAR)



### 239 **3.2 Problematic**

240 The excavation of the river involves suspended sediment release.  
241 Depending on the concentration of these sediments at the filtration  
242 plant, in the city of Jonquiere, can be harmful, which eventually leads  
243 to a significant risk of drinking water pollution and therefore a health  
244 risk for the population.

245 Suspended sediment concentration at the Jonquiere water intake  
246 should be less than 19.29 mg/l to ensure delivering drinkable water.  
247 To minimize suspended transport downstream the Pibrac Bridge,  
248 cofferdams were installed just after the bridge (figure 5). The question  
249 to be answered is, for a given constant discharge controlled by the  
250 Pibrac dam, km 11.1, what is the maximum sediment concentration  
251 released at the bridge to ensure that the suspended sediment  
252 concentration at the Jonquiere water intake is less than 19.29 mg/l?

253

### 254 **3.3 Available data**

255 Some data are easily retrieved such as river bathymetry, upstream and  
256 downstream boundary conditions, river bed composition, and  
257 geometry of cross-sections describing the river. All these data were  
258 secured by GENIVAR thanks to the field campaigns carried out on the  
259 site.

260

261    **Turbidity**

262    Turbidity surveys were done at various locations along the river. A  
263    turbidity probe was installed in Aux Sables River near Highway 70, 1  
264    km upstream of the Jonquiere water intake. Moreover, turbidity  
265    measurements took place at three sites (figure 7), Jonquiere water  
266    intake (site A), near the CEPAL rapids (site B) and just upstream of  
267    the Pibrac bridge (site C).

268

269    **Boundary condition**

270    The upstream condition is located just after the Pibrac Bridge, km  
271    10.3, where the discharge will be specified. The discharge in the river is  
272    controlled by the Pibrac dam, km 11.1. During the work period, the  
273    released discharge from Lake Kenogami is quasi-permanent, varying  
274    between 5 m<sup>3</sup>/s and 50 m<sup>3</sup>/s. For the downstream boundary condition,  
275    at the Jonquiere dam, km 3 (figure 2), the water level is maintained  
276    constant by the dam at 140.2 m.

277    There is no internal boundary condition for the water phase. For the  
278    suspended sediment, a concentration, depending on the water  
279    discharge, will be specified at km 5.4.

280

281

282

283 **Riverbed composition**

284 The armored riverbed is made of large pebbles with the exception of  
285 rapids, where water flows over bedrock. There would be no bed load  
286 sediment transport. During riverbed excavations, the cohesive  
287 sediment, beneath the armored layer, was release and transported  
288 downstream.

289

290 **Cross-sections**

291 The river reach from the Pibrac Bridge, km 10.3, to the Jonquiere  
292 dam, km 3.0, is discretized into 86 cross-sections provided by  
293 GENIVAR.

294

295 **Water lines**

296 GENIVAR provided the water lines corresponding to the following  
297 discharges: 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 m<sup>3</sup>/s.

298

299 **3.4 Numerical model**

300 **UMHYSER-1D**

301 For a constant water discharge, released from Lake Kenogami, the  
302 convection-diffusion equation is solved to determine the concentration

303 of suspended sediments at the Jonquiere water intake. To this end, the  
304 software UMHYSER-1D (AlQasimi and Mahdi, 2018), presented in a  
305 companion paper, is used. For unsteady sediment transport,  
306 UMHYSER-1D solves the convection-diffusion equation with source  
307 term from sediment erosion/deposition:

$$\frac{\partial AC}{\partial t} + \frac{\partial (\xi QC)}{\partial x} = \frac{\partial}{\partial x} \left( AD \frac{\partial C}{\partial x} \right) + \Sigma \quad (1)$$

308  
309 where:  $C$  = depth averaged concentration;  $A$  = cross section area,  $Q$  =  
310 flow rate,  $D$  = longitudinal diffusion coefficient, a calibration  
311 parameter,  $\xi$  = velocity of sediment relative to the water (Greimann et  
312 al., 2008).  $\Sigma$  = source (erosion, excavation, lateral inflow) and sink  
313 (deposition) terms for one sediment class.

314 To discretize the convective term, the Lax-Wendroff TVD scheme is  
315 used, and a central difference scheme is used to for the diffusion term  
316 (Tannehill et al., 1997). The source term is discretized according to  
317 the procedure used for the BASEMENT model (Vetsch et al., 2017).

318

#### 319 **4 Results and discussion**

320 Numerical modeling of the Aux Sables River should answer the  
321 following question: under which hydraulic conditions (flows) the  
322 concentration of the sediments, released at Pibrac bridge, would be

323 lower than 19 mg/l at the filtration station (water intake) of the city of  
324 Jonquiere?

325

326 To answer this question, the following numerical simulations are  
327 made:

328 - Permanent flow modeling without sediment transport: this step is  
329 necessary for the determination of the Manning coefficients,  
330 - Modeling of suspended transport (released sediments): first, calibrate  
331 the model to determine the right diffusion coefficient. Then, the  
332 validation of the model is undertaken.

333 - Use of the model to assess suspended sediment transport and answer  
334 the previous question.

335

#### 336 **4.1 Calibration and validation**

##### 337 **Liquid phase**

338 Knowing the flow discharges and the corresponding water lines,  
339 simulations are carried out for a steady flow at different discharges  
340 and the results are compared to measurements of water lines. For each  
341 of the available discharges (5, 10, 15, 20, 25, 30, 35, 40, 45 and 50  
342 m<sup>3</sup>/s), the maximum difference between observed and simulated water  
343 lines does not exceed 3 cm for the Manning's coefficients listed in

344 table 2. Figure 10 shows an example of the calibration for a discharge  
345 of 30 m<sup>3</sup>/s.

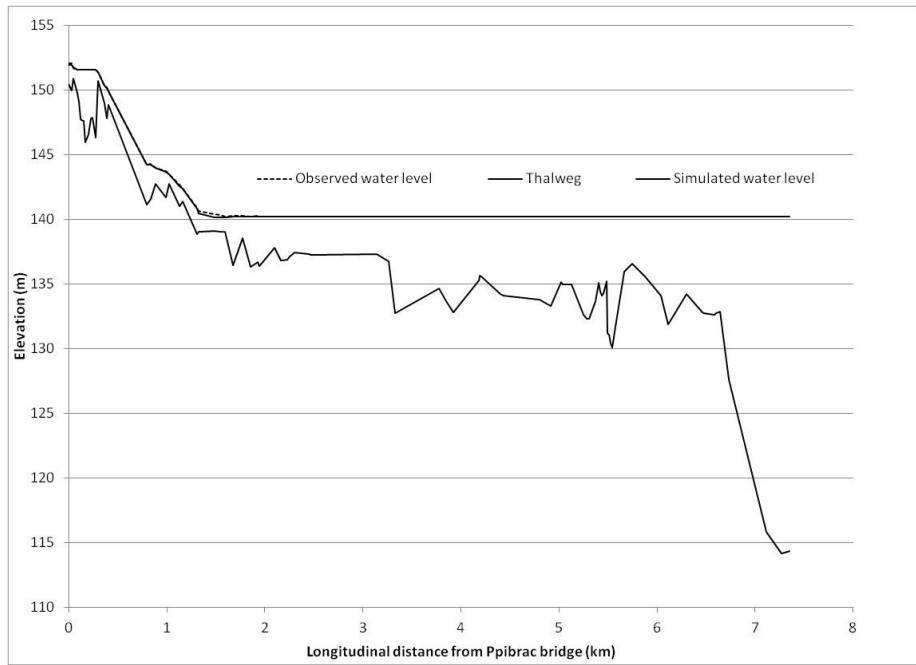
346

347 Table 2. Calibrated Manning's coefficients

River km	Right bank	River	Left bank
0 - 5.3	0.08	0.03	0.08
5.3 - 6.2	0.08	0.03	0.04
6.2 - 9.0	0.06	0.03	0.04
9.0 - 10.0	0.08	0.05	0.08
10.0- 10.3	0.06	0.02	0.06

348

349



350

351 Figure 10. Example of calibration results for a discharge of 30 m<sup>3</sup>/s.

352

353

354

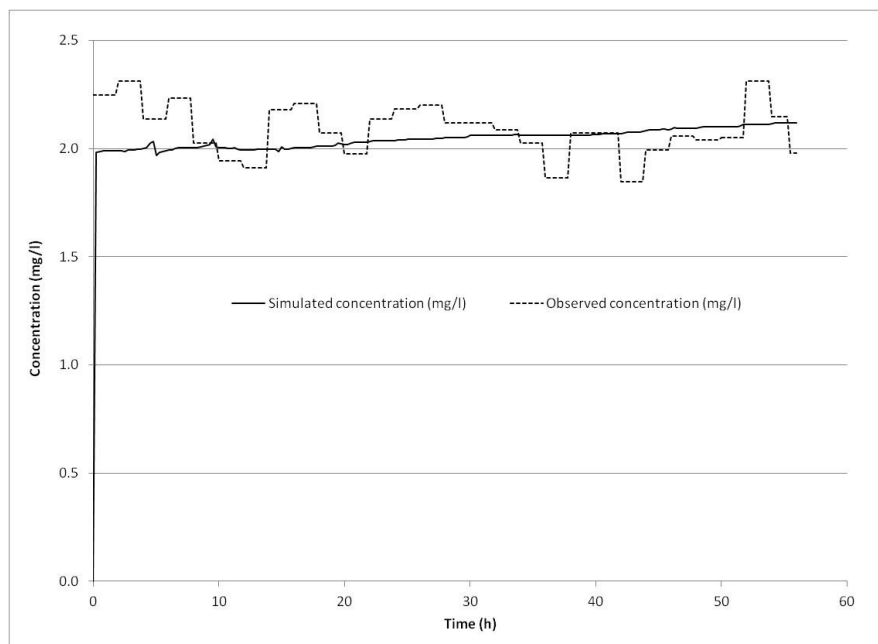
355

356

357

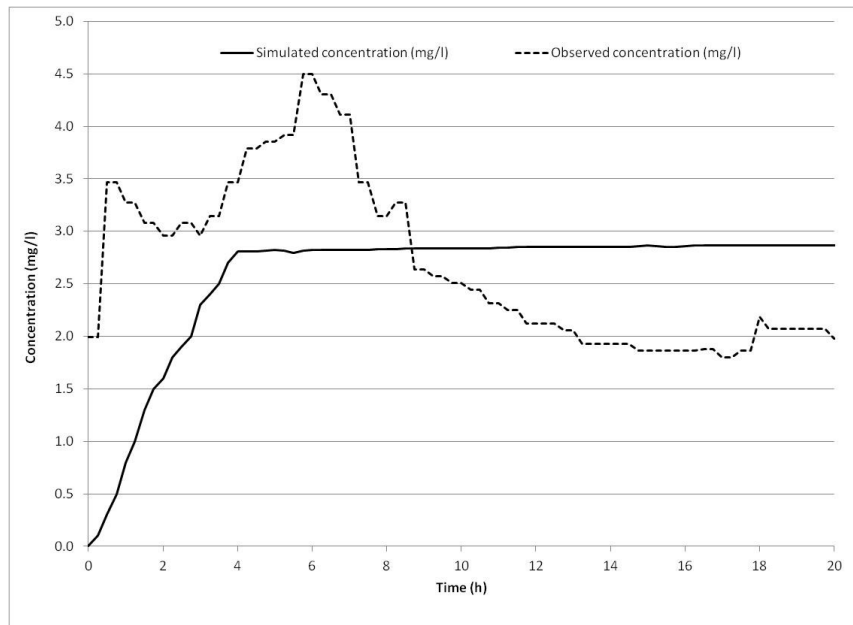
**Solid phase**

358 From March 13-16, 2009, no rain was observed, thus the sediments  
359 input from the tributary at km 5.4 is assumed nil. The river discharge  
360 is almost constant, varying between 24.7 m<sup>3</sup>/s and 26.4 m<sup>3</sup>/s, and the  
361 observed turbidity, at km 6.15, varies between 1.43 and 1.95 NTU.  
362 The calibration is achieved by varying the diffusion coefficient given  
363 by Fischer's equation (Fisher, 1975). The best results (Figure 11) are  
364 obtained by changing the proportionality constant of Fisher's equation  
365 from 0.011 to 0.0135. Note that the simulated concentration starts at 0  
366 mg/l since the model's computations start with a nil concentration.  
367 Figure 12 shows a validation example for the period March 2-3, 2009.  
368



369

370 Figure 11. Calibration of the diffusion coefficient for a liquid  
 371 discharge varying between 24.7 m<sup>3</sup>/s and 26.4 m<sup>3</sup>/s during the period  
 372 March 13-16, 2009.  
 373



374  
 375 Figure 12. Validation of the calibrated model. Observed and simulated  
 376 concentration from March 2, 22:00 to March 3, 18:00.  
 377

## 378 4.2 Suspended sediment assessment

379 To find the maximum sediment concentration to be released at the  
 380 bridge to ensure that the suspended sediment concentration at the  
 381 Jonquiere water intake is less than 19.29 mg/l, the calibrated and  
 382 validated model will be used.

383 According to the available means on the site, the maximum possible  
 384 quantity of suspended sediment to be released at the Pibrac bridge is  
 385 53.80 tons per day. If we report this over an hour of work, that's



386 2.2419 tons dumped. It is therefore considered that during the works,  
387 the maximum sediment discharge released does not exceed 2.5 tons  
388 per hour.

389 A series of simulations are performed as follow:

- 390 a- The sediment discharge is constant equal to 2.5 tons/h;  
391 b- Several simulation are performed, each with a different water  
392 discharge, looking for the minimum water discharge giving a  
393 concentration at the water intake, at Jonquiere, of 19.29 mg/l.  
394 c- Redo step b) with a smaller sediment discharge (2, 1.5, 1, 0.5  
395 tons/h) looking for the corresponding minimum water discharge

396 Table 3 and Figure 13 summarize the results. According to the  
397 available river discharge, controlled by the Pibrac dam, one can decide  
398 what's the maximum quantity to be released into the river.

399  
400 Table 3. Maximum tolerable released sediment load into the Aux  
401 Sables River

Upstream released sediment (ton/h)	Minimum water discharge (m <sup>3</sup> /s)	Concentration at water intake (mg/l)
0.5	5	19.15
1.0	10	19.10
1.5	18	19.13
2.0	25	19.08
2.5	32	18.96

402  
403

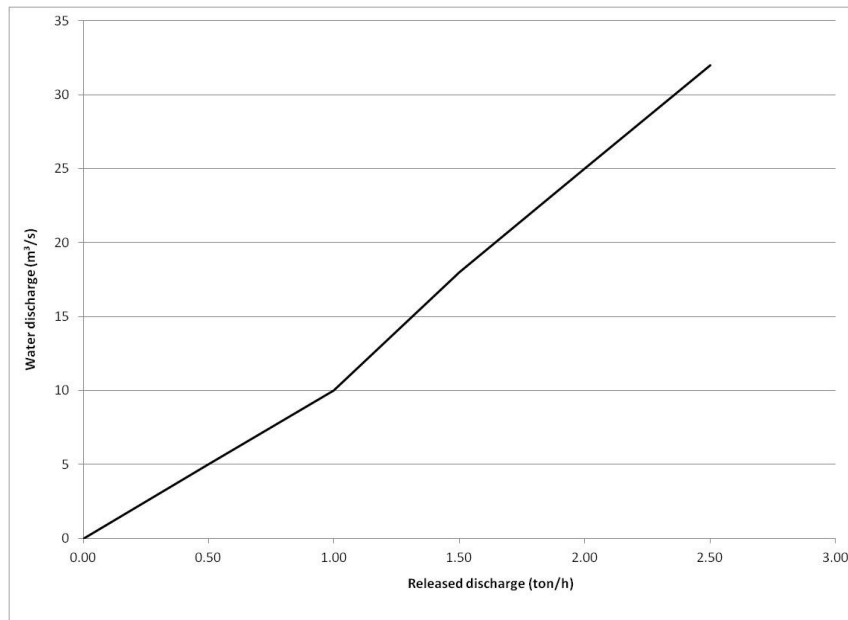


Figure 13. Maximum sediment load released upstream corresponding to the minimum water discharge of the Aux Sables River.

## 5 Conclusion

The severe rainstorm of July 1996, caused extreme flooding in the Saguenay region, Quebec. Among its numerous consequences, along the Aux Sables River, the flood discharges exceeded the design or available spilling capacity at two run-of-the river dams. Flooding in an urban area damaged or destroyed buildings and infrastructures. The inundation threshold discharge was exceeded by a factor of 3.8.

The retained option for flood mitigation on Aux Sables River consists of increasing the flow section downstream of Pibrac bridge by

419 excavating the left bank for a length of about 60 m; increasing the  
420 flow section to the right of the bridge by excavating the river bed of  
421 about 2 m and excavating on the left bank; replacing the Pibrac Bridge  
422 with a span of 50 m (without central pillar) and increasing the flow  
423 section upstream of the bridge by excavating a channel of 440 m  
424 length, with a maximum width of 60 m, and requiring an excavation  
425 of the river bed varying from 0.5 to 2 m.

426 This option raised pollution risk at the water intake at Jonquiere city,  
427 located a few kilometers downstream the work area. Thanks to a  
428 newly developed software, UMHYSER-1D, suspended sediment  
429 impact assessment in Aux Sables River provides the maximum  
430 permissible sediment discharge to be released in the river to avoid any  
431 pollution risk for the population of Jonquiere city. Using UMHYSER-  
432 1D to mitigate water pollution risk confirms the important role of  
433 numerical modeling in solving complex engineering problems.

434

#### 435 **Acknowledgement**

436 This research was supported in part by a National Science and  
437 Engineering Research Council (NSERC) Discovery Grant, application  
438 No: RGPIN-2016-06413. The authors would like to acknowledge the  
439 contribution of Mr. Denis Careau, Director of the Renewable Energy

440 Development Branch at Ministère de l'Énergie et des Ressources  
441 naturelles, Québec. Special thanks to the management of WSP's  
442 Power Unit, which has greatly facilitated collaboration between  
443 industry and academics in this project. This collaboration helps to  
444 perfect the training of engineers and scientists on certain issues related  
445 to water and the effects of climate change.

446  
447

448

449

450

#### 451 **References**

452 AlQasimi, E., and Mahdi, T. (2018). Unsteady Model for the  
453 Hydraulics of Sediments in Rivers. 26th Annual Conference of  
454 the Computational Fluid Dynamics Society of Canada. June 10-  
455 12, Winnipeg, MB, Canada. Accepted, May 20, 2018.

456 Brooks, G.R., Lawrence, D.E., K. Fung, C. Begin and D. Perret  
457 (1997). Flooding from the July 18-21, 1996 rainstorm in the  
458 Saguenay area, Quebec: fluvial geomorphic effects and slope  
459 stability along selected major river reaches. Geological Survey of

460 Canada, open file 3498. Report prepared for Emergency  
 461 Preparedness Canada, 81 p. + appendices.

462 Brooks, G.R., and Lawrence, D.E. (1999). The drainage of the Lake  
 463 Ha! Ha! reservoir and downstream geomorphic impacts along Ha!  
 464 Ha! River, Saguenay area, Quebec, Canada. *Geomorphology* 28.  
 465 141–168.

466 Brooks, G.R., and Lawrence, D.E. (2000). Geomorphic Effects of  
 467 Flooding Along Reaches of Selected Rivers in the Saguenay  
 468 Region, Quebec, July 1996. *Géographie physique et Quaternaire*  
 469 54, 281-299.

470 Commission scientifique et technique sur la gestion des barrages  
 471 (CSTGB) (1997). Rapport: Commission scientifique et technique  
 472 sur la gestion des barrages. Québec, Janvier 1997, Gouvernement  
 473 of Québec, 241 p. + annexes.

474 Environnement et Faune Quebec (1996). Gestion du Lac Kenogami et  
 475 des autres lacs-reservoirs; Direction de l'hydraulique. Le 17 aout  
 476 1996, 80 p. + annexes.

477 GENIVAR (2002). Projet de régularisation des crues du bassin versant  
 478 du lac Kénogami – Note technique sur le calcul des gains et pertes  
 479 d'habitat et de production de l'Ombre de fontaine, 10 pages et  
 480 annexes.

481 GENIVAR. 2009. Augmentation de la capacité d'évacuation de la  
 482 rivière aux Sables dans le secteur du pont Pibrac - Rapport pour la  
 483 demande de modification du décret 481-2007. Rapport de  
 484 GENIVAR Société en commandite présenté au ministère des  
 485 Ressources naturelles et de la Faune. 19 p. et annexes.

486 Greimann, B., Lai, L., and Huang, j. (2008). Two-Dimensional Total  
 487 Sediment Load Model Equations. *Journal of Hydraulic*  
 488 *Engineering*, ASCE, Vol. 134(8), 1142-1146.

489 Hydro-Québec (2001). Gestion des crues extrêmes du lac réservoir  
 490 Kénogami – Rivière aux Sables à 650 m<sup>3</sup>/s, canal de protection  
 491 contre l'inondation des résidences du secteur à l'amont du pont  
 492 Pibrac, rapport sectoriel, novembre 2001, 104 pages.

493 Hydro-Québec (2002a). Étude de rupture des digues et des barrages  
 494 du réservoir Pikauba et du lac Kénogami, mars 2002, 41 pages,  
 495 cartes et figures.

496 Hydro-Québec (2002b). Projet de régularisation des crues du bassin  
 497 versant du lac réservoir Kénogami. Étude de géomorphologie,  
 498 rapport sectoriel, mai 2002, 89 pages et annexes.

499 Lapointe, M., Driscoll, S., Bergeron, N., Secretan, Y., et Leclerc, M.  
 500 (1998). Response of the Ha! Ha! River to the flood of July

501 Saguenay Region of Quebec: Large-scale avulsion in a river  
502 valley. *Water Resources Research*, 34(9): 2383–2392.

503 Ministère des Ressources Naturelles, de la Faune et des Parcs(2003).  
504 Synthèse des études réalisées sur les variantes de projet, mai  
505 2003, 2 pages.

506 Ministère des Ressources Naturelles et Hydro-Québec (2002a).  
507 *Documentation relative à l'étude d'impact sur l'environnement*  
508 *déposée au ministre de l'Environnement. Volume 1 – Vue*  
509 *d'ensemble*, janvier 2002, pages 1-1 à 9-2 et annexes.

510 Ministère des Ressources Naturelles et Hydro-Québec (2002b).  
511 *Documentation relative à l'étude d'impact sur l'environnement*  
512 *déposée au ministre de l'Environnement. Volume 2 –*  
513 *Aménagement du réservoir Pikauba*, janvier 2002, pages 1-1 à 9-  
514 13 et annexes.

515 Ministère des Ressources Naturelles et Hydro-Québec (2002c).  
516 *Documentation relative à l'étude d'impact sur l'environnement*  
517 *déposée au ministre de l'Environnement. Volume 3 – Sécurisation*  
518 *du pourtour du lac Kénogami*, janvier 2002, pages 1-1 à 14-4 et  
519 annexes.

520 Ministère des Ressources Naturelles et Hydro-Québec (2002d).  
521 *Documentation relative à l'étude d'impact sur l'environnement*

522        *déposée au ministre de l'Environnement. Volume 4 –*  
523        *Aménagement d'un seuil dans la rivière aux Sables, janvier 2002,*  
524        *pages 1-1 à 8-2 et annexes.*

525    Ministère des Ressources Naturelles et Hydro-Québec (2002e).  
526        Complément de l'étude d'impact sur l'environnement. Évaluation  
527        des effets cumulatifs, septembre 2002, 78 pages.

528    Tannehill, J. C., Anderson D. A. and Pletcher, R. H. (1997).  
529        *Computational Fluid Mechanics and Heat Transfer*, 2nd Edition,  
530        *Taylor & Francis Ltd.*, Washington DC.

531    Vetsch, D., Rousselot, P., Volz, C., Vonwiller, L., Peter, S., Ehrbar,  
532        D., and Mueller, R. (2017). System Manuals of BASEMENT,  
533        Version 2.7. Laboratory of Hydraulics, Glaciology and  
534        Hydrology, ETH Zurich.

535